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(54) Abstract Title

Optical network with wavelength converted protection paths

(57) An optical network comprises a plurality of nodes (402), including a first node A and a second node D; a working path from the first node A to the second node D; a protection path, different from the working path, from the first node A to the second node D; a switch; and a wavelength converter (405); wherein, during normal operation, working signals for transmission from the first node A to the second node D are transmitted via the working path, each such working signal having a wavelength within a working range of wavelengths; and wherein, during protection-switched operation, the switch is operable to switch such working signals destined for the second node D away from the working path and onto the protection path, and the wavelength converter is operable to convert such switched signals into protection signals, each such protection signal having a wavelength within a protection range of wavelengths, different from the working range of wavelengths, such that the protection signals can then be transmitted to the second node D via the protection path. Alternatively, working signals may be converted by phase conjugation means into protection signals having a phase-conjugate relationship to the working signals.

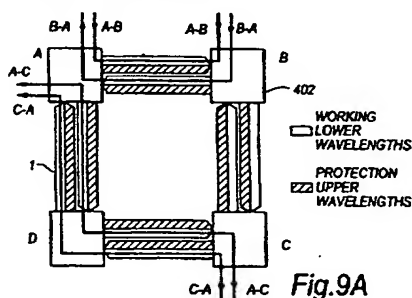


Fig.9A

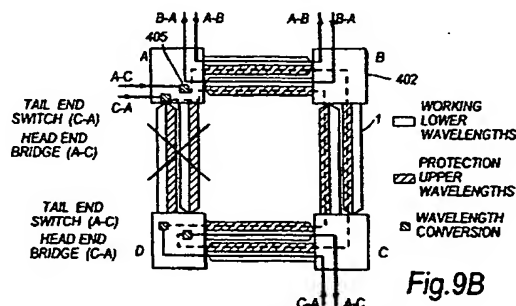
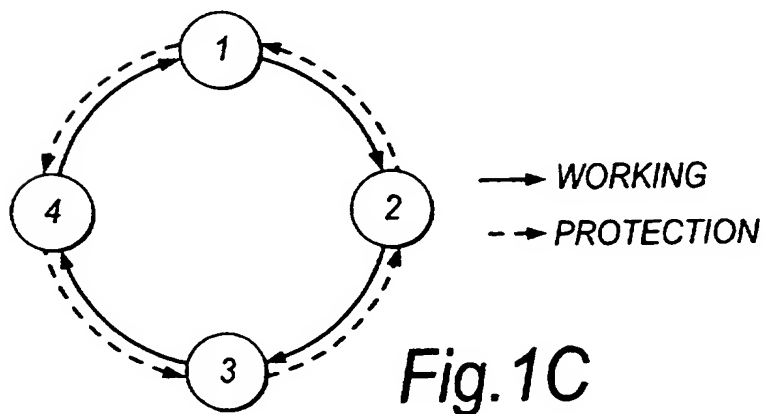
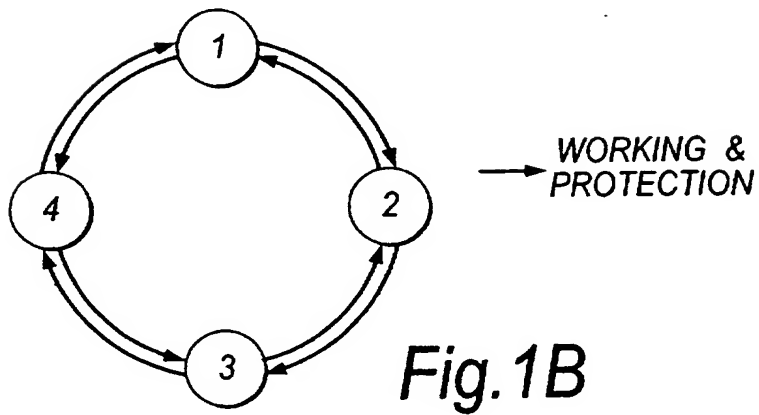
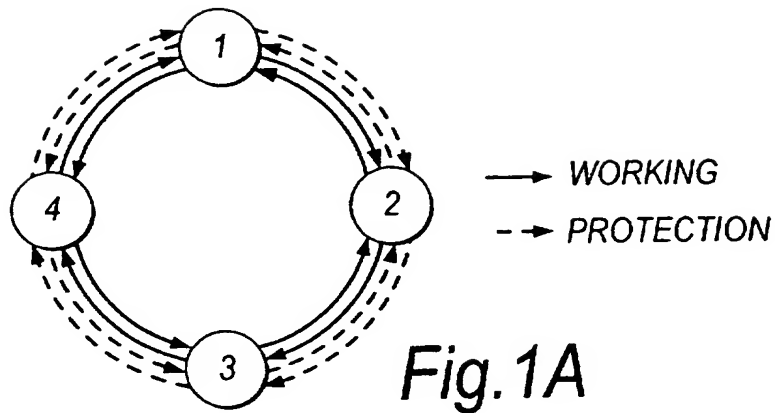


Fig.9B

At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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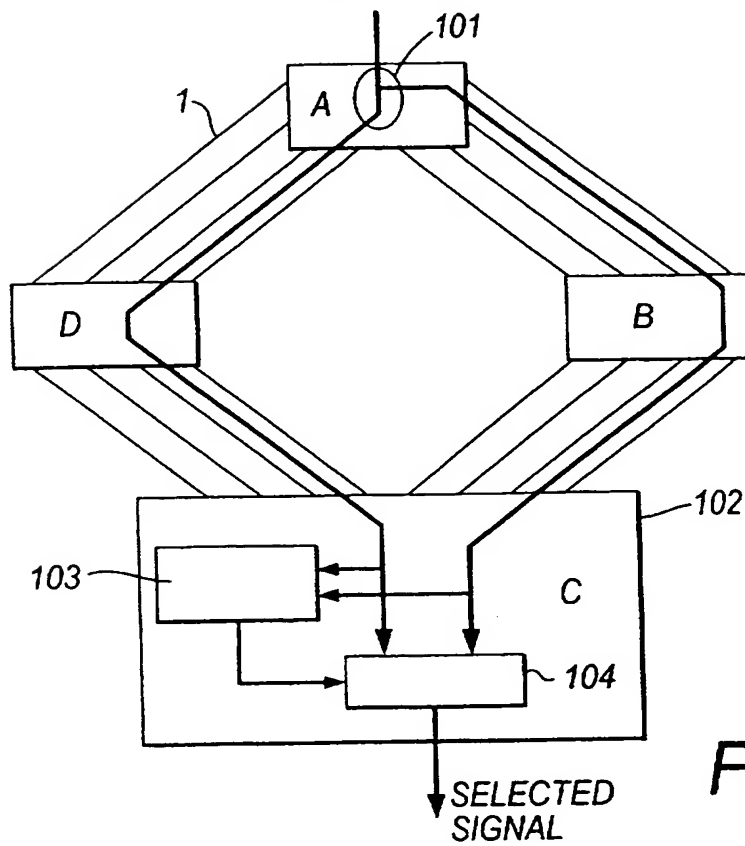


Fig. 2A

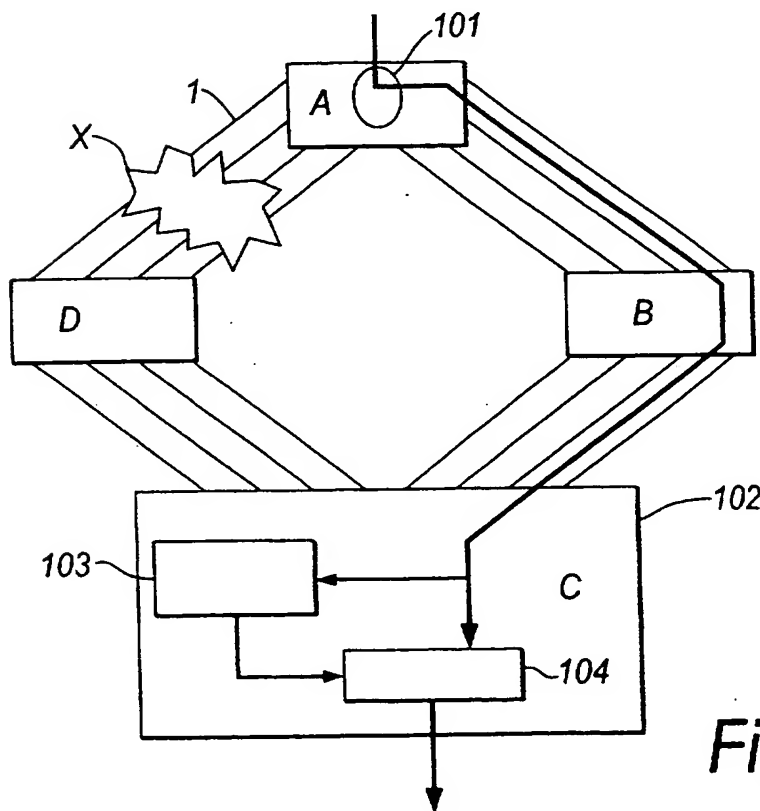
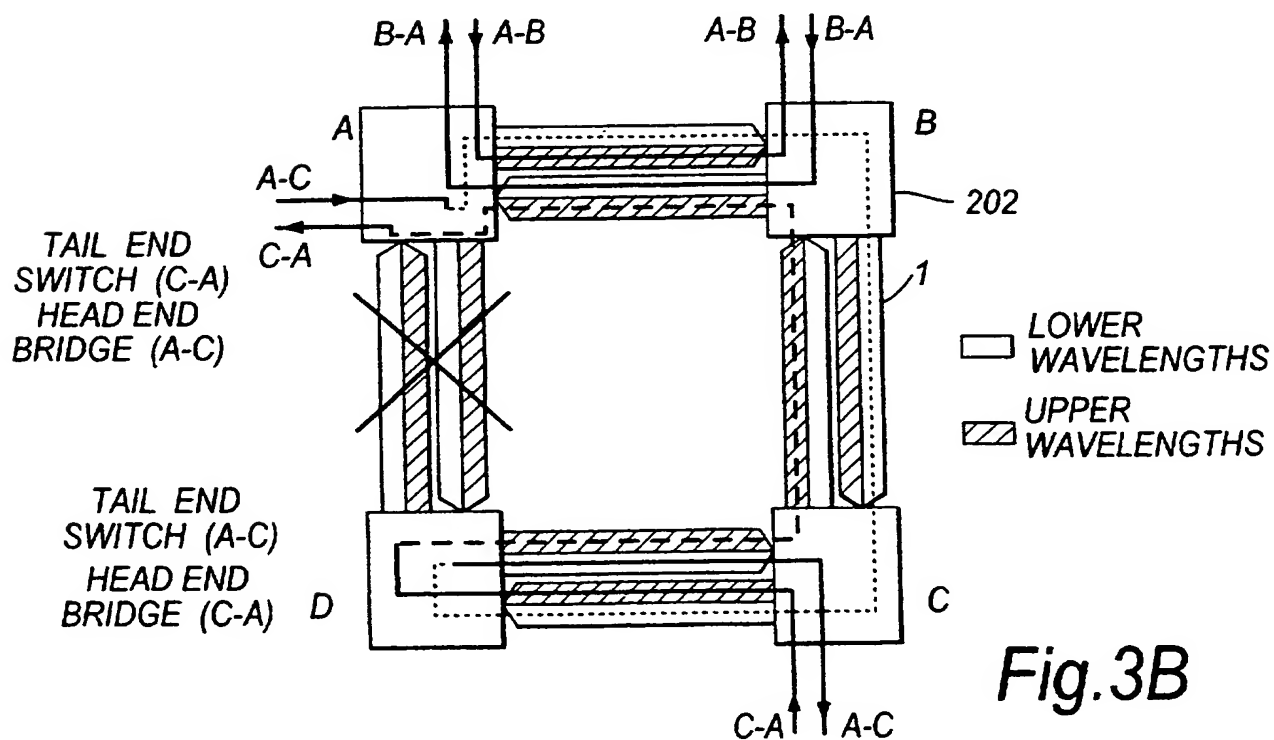
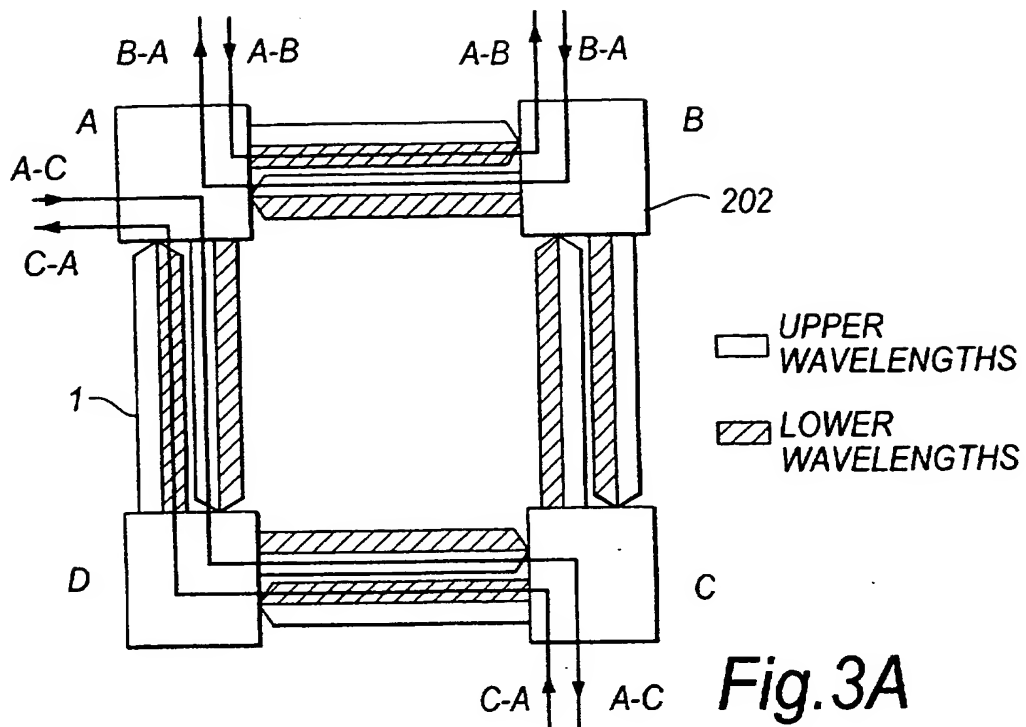


Fig. 2B



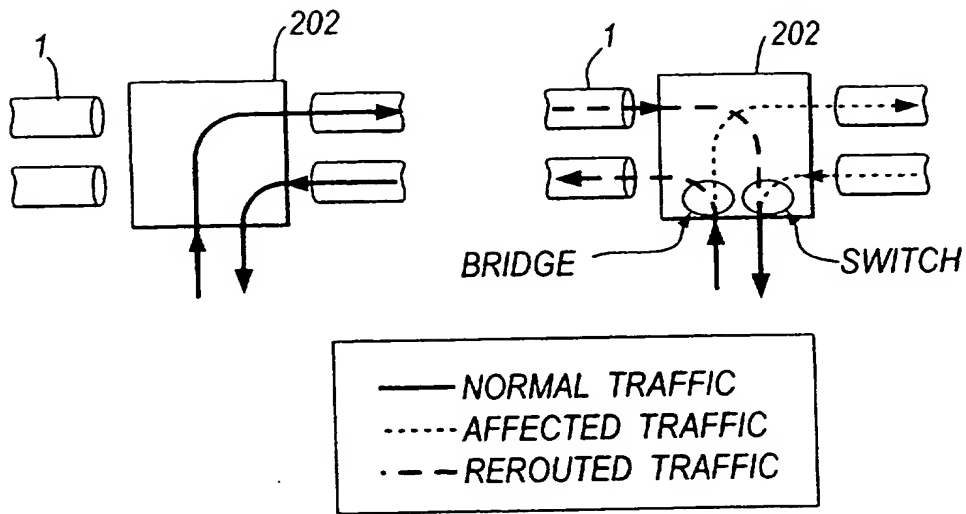


Fig.4

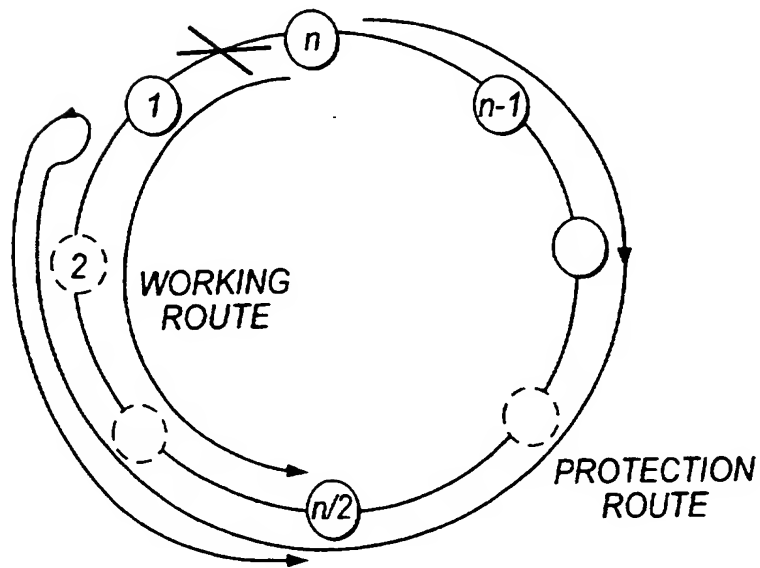


Fig.5

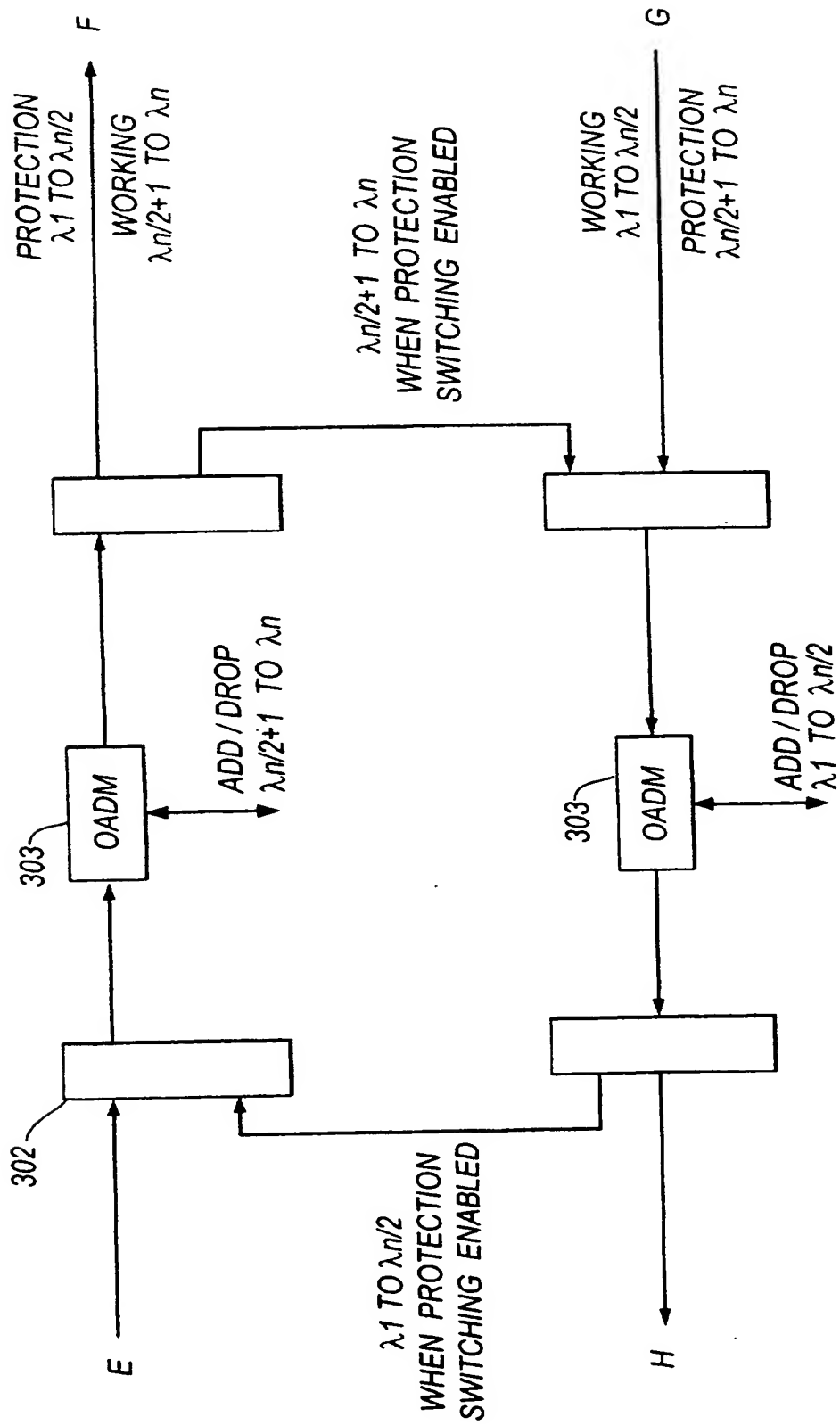


Fig.6

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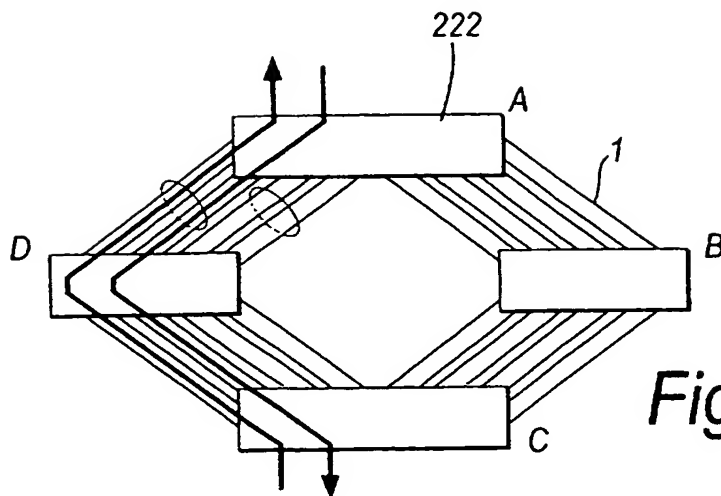


Fig. 7A

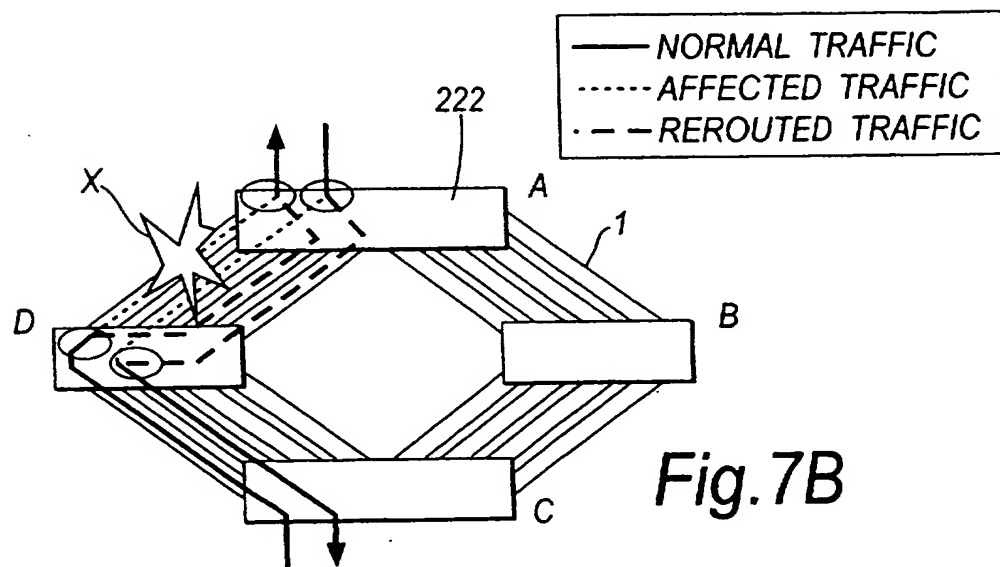


Fig. 7B

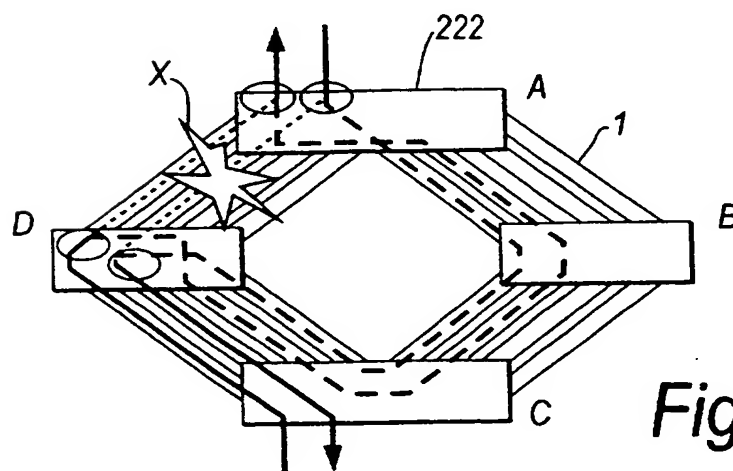


Fig. 7C

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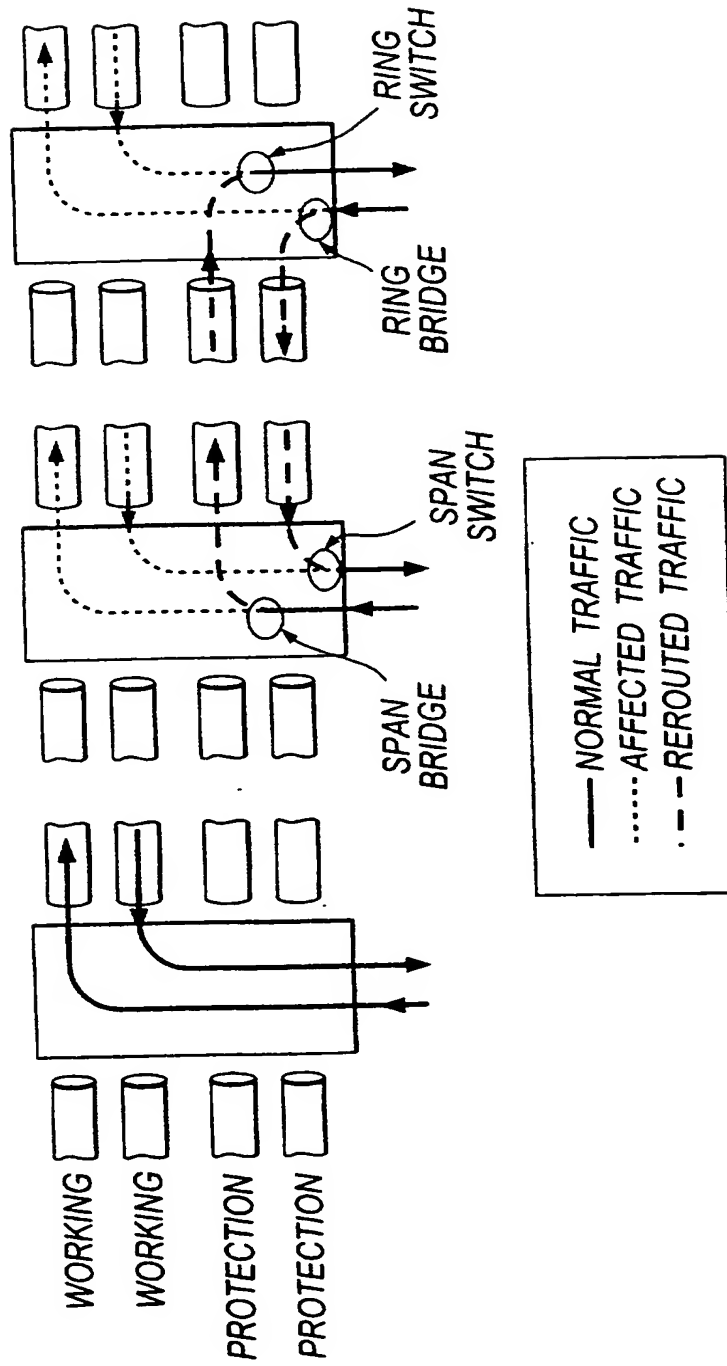
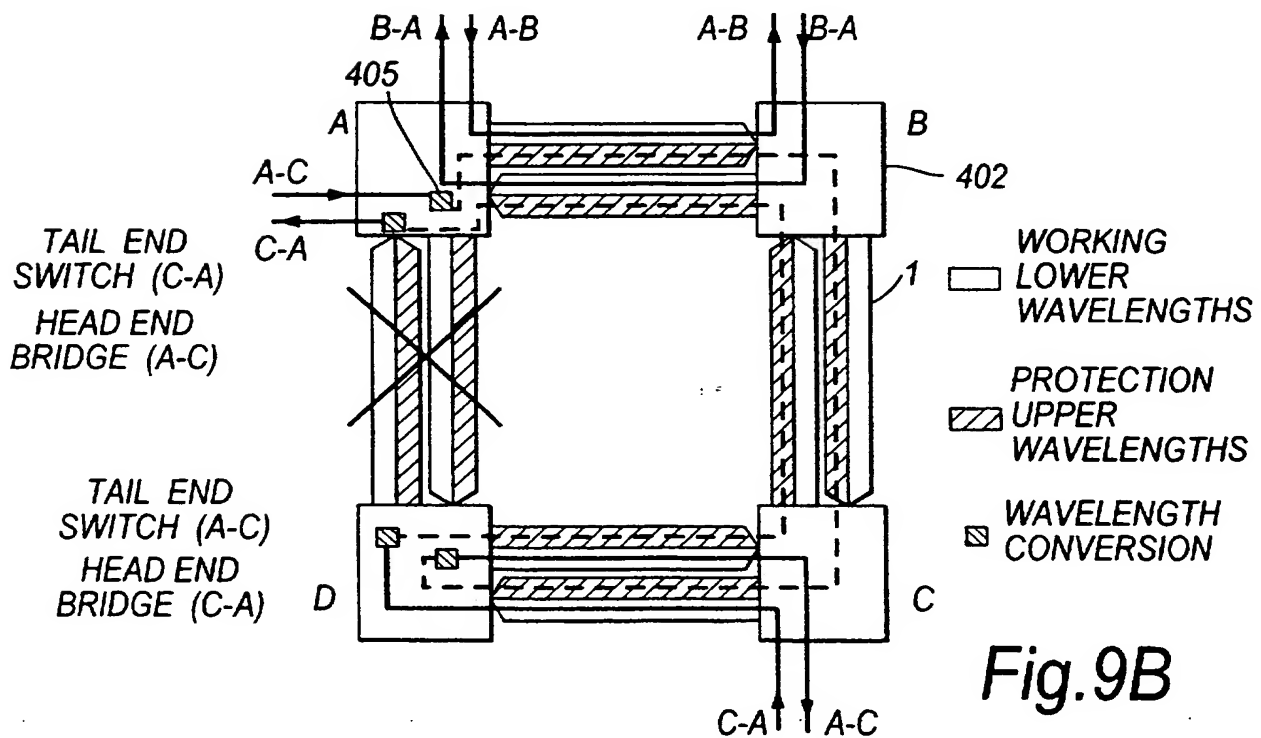
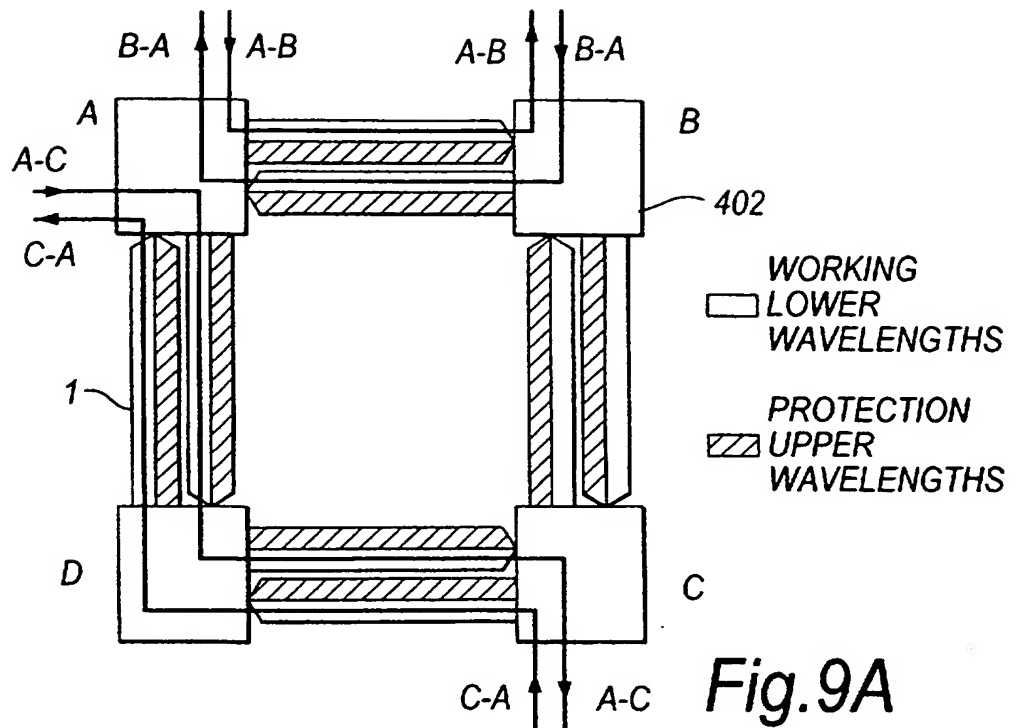


Fig.8



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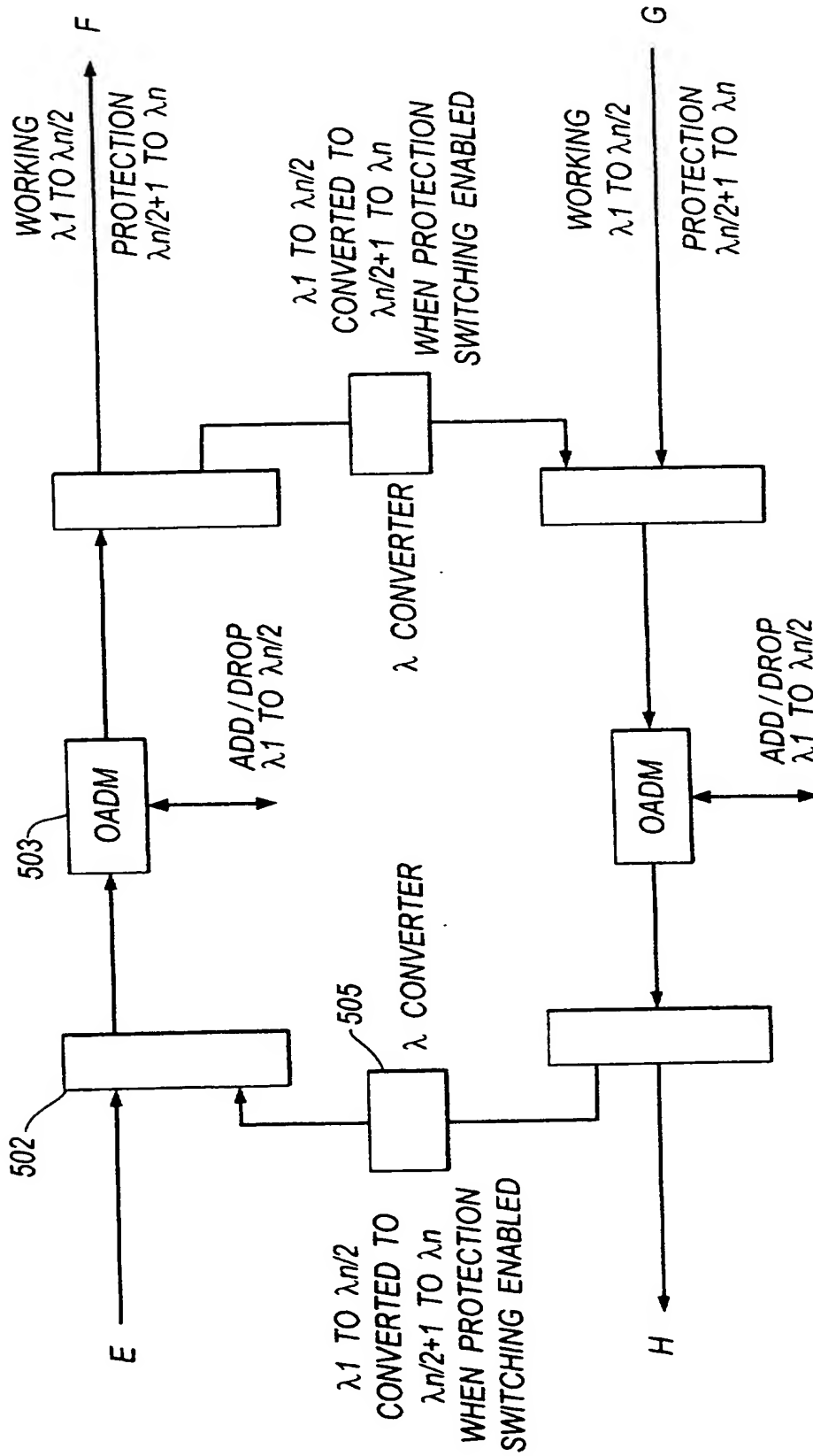


Fig.10

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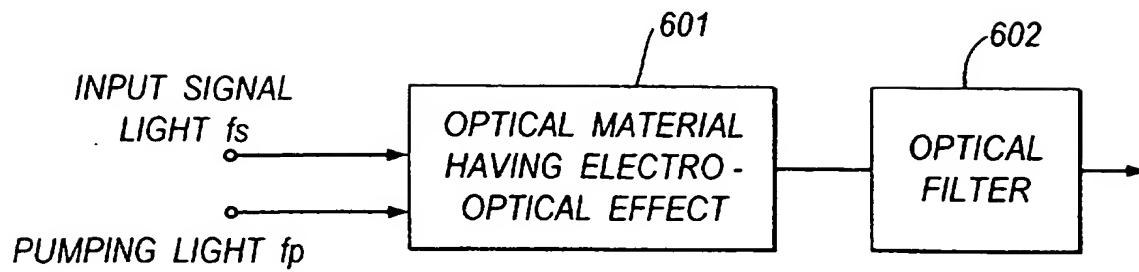


Fig.11A

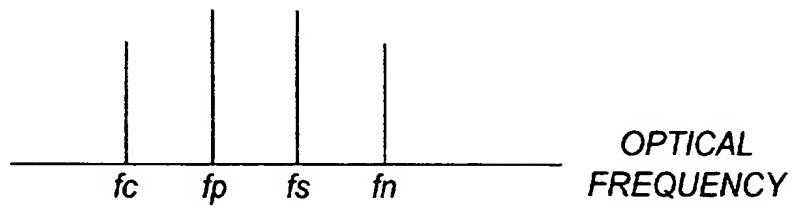


Fig.11B

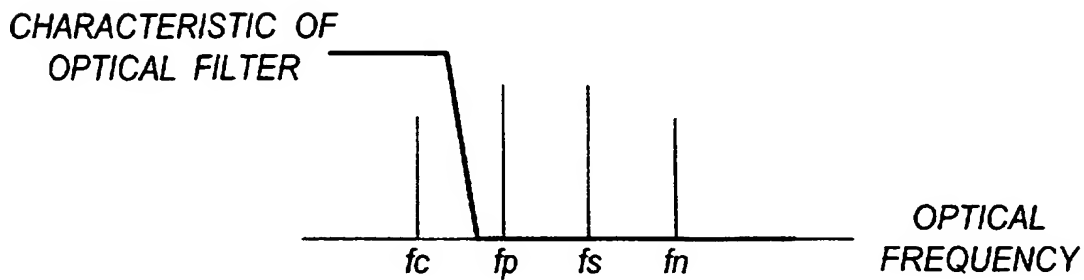


Fig.11C

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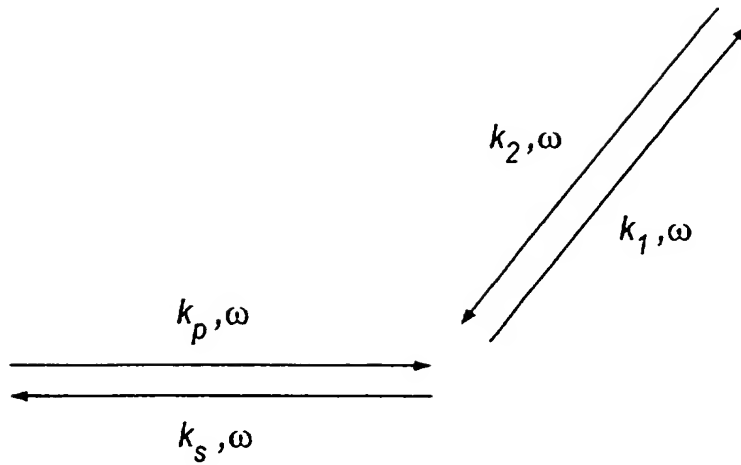


Fig.12A

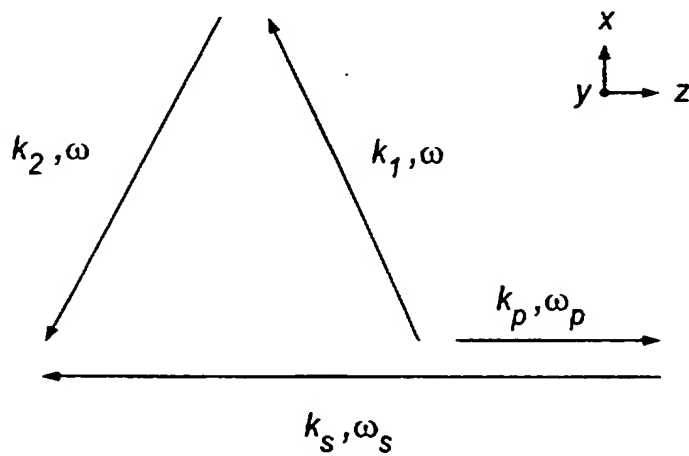


Fig.12B

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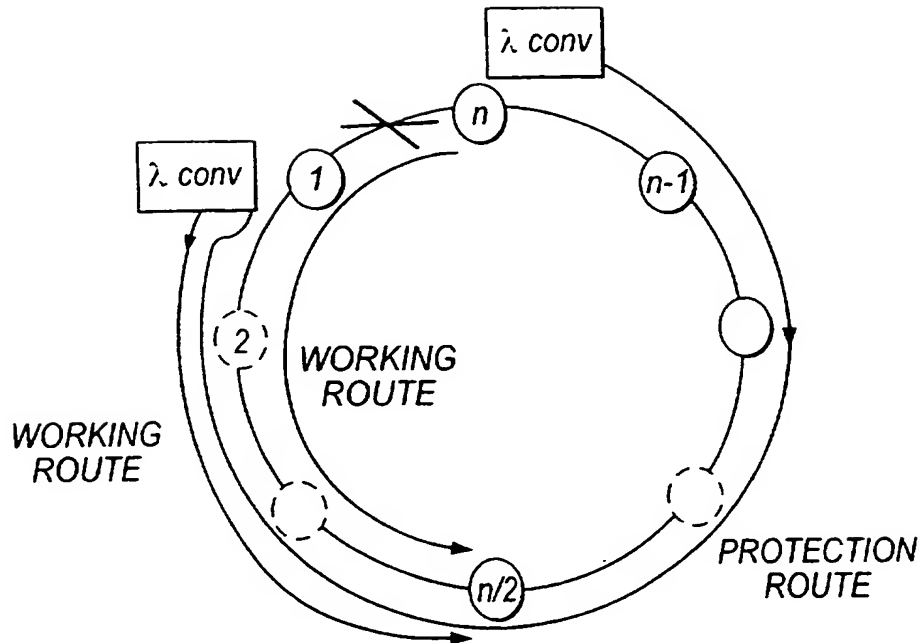


Fig.13A

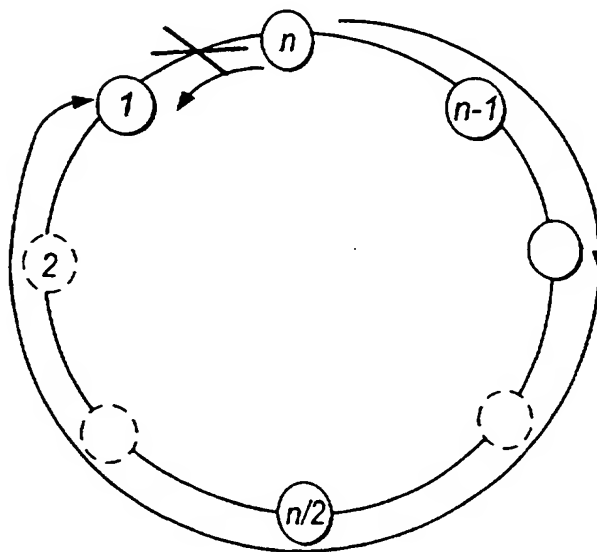


Fig.13B

OPTICAL NETWORKS

This invention relates to optical networks, and particularly to survivability in optical networks.

Survivability and reliability have always been important factors in communications networks. As companies expand their networks and consolidate resources, survivability and reliability become even more important requirements. The integrity of the public network is an issue of increasing concern to all segments of the telecommunications industry, and network failures covering widespread geographic areas can affect millions of users. Such network disasters can occur as a result of physical damage, or failures in software or control systems. For example in Scarborough in 1990, a fire cut service to 23,000 exchange lines, affecting around 100,000 subscribers.

To minimise the impact any inevitable failures will have on a network's end users, network survivability techniques should be applied to a network architecture and the systems that make up the network. Protection switching is one set of methods by which spare resources, for example an alternate fibre route plus optical transmitters and receivers at each end, are put into service following a particular failure, such as a fibre cut. Within an overall network, protection switching can be applied to some aspects in conjunction with other survivability techniques, such as re-routing and self-healing networking, to offer a complete service survivability solution.

In many cases, the particular survivability technique is based on the inherent capabilities of the network. For instance, SONEts (Synchronous Optical NETworks) make use of SONET protection schemes that are based on standard SONET overhead bytes and messaging

channels.

There are various network topologies and configurations, including point-to-point, hubbed, linear add-drop, and ring configurations, and existing
5 network protection schemes used on these topologies can be broadly categorised into three categories: protection switching, re-routing, and self-healing. Each of these is summarised below.

Protection switching is the establishment of a
10 pre-assigned replacement connection by means of equipment without the centralised network management control function. Protection switching is a mechanism provided within the SONET specification that is designed to provide duplicate fibre span paths. In
15 this configuration, a backup fibre span (protection fibre) is enabled when and if there is a failure within the fibre span currently carrying traffic on a SONET network.

There are essentially two types of protection switching architectures: a 1+1, and an m:n type. In
20 the 1+1 architecture type, a protection entity is dedicated to each working entity, and the working entity is bridged onto the protection entity at the source endpoint of the protected domain. The traffic
25 on working and protection entities is transmitted simultaneously to the sink endpoint of the protected domain where a selection between the working and protection entity is made based on some predetermined criteria, such as a server defect indication.

30 In the m:n architecture type, m dedicated protection entities are shared by n working entities, where typically m is less than or equal to n. The bandwidth of each protection entity should be allocated in such a way that it may be possible to protect any of
35 the n working entities in case at least one of the m protection entities is available. When a working

entity is determined to be impaired, it must be first assigned to an available protection entity followed by transition from the working to protection entity at both the source and sink end points of the protected domain. Note that when more than m working entities are impaired, only m working entities can be restored. Also note that the 1+1 protection switching architecture is a form of 1:1 protection switching with the head end permanently bridged.

Protection switching can be used on any physical topology. A similar mechanism may also be applied at, for example, the ATM (Asynchronous Transfer Mode) layer.

Re-routing network architectures use a centralised control scheme, establishing a replacement connection by use of the centralised network management control connection.

With self-healing networks, the establishment of a replacement connection is made by the network in a distributed fashion without the centralised network management control function.

It should be noted that in practice the boundaries between the above three network protection schemes are not firmly established, nor should they be. For example the self-healing ring configuration can use the protection switching mechanism. The self-healing ring configuration is the most commonly deployed topology in mission critical government and enterprise backbones, due to its survivability characteristics. A self-healing ring configuration will now be described in more detail.

A self-healing ring guards against fibre cuts without using the more expensive technique of 1:1 protection switching with diverse routing. It also reduces the number of nodes required for the same traffic by allowing fibre capacity to be shared. Using

these rings, network survivability and availability are improved, whilst reducing cost.

The self-healing ring can generally be divided into two categories: bidirectional self-healing rings (B-SHRs) and unidirectional self-healing rings (U-SHRs). The type of ring depends upon the path travelled by a duplex communication channel between each office pair. The SHR is called a bidirectional SHR if both directions of a duplex channel travel over the same path, and a unidirectional SHR if each direction of a duplex channel travel on different paths. For example in Figures 1A and 1B of the accompanying drawings, both directions of a duplex channel between offices 2 and 4 use the same path which travels through office 3, and hence both these figures illustrate B-SHRs. For the case of a U-SHR (Figure 1C) a duplex channel between offices 2 and 4 travels over two opposite paths: 2->3->4, and 4->1->2. Thus a B-SHR requires two working fibres to carry a duplex channel, and a U-SHR requires only one working fibre to carry a duplex channel. In order to provide a protection capability for fibre system failures and fibre cable cuts, a B-SHR may use four fibres (one working fibre pair and one protection fibre pair) or two fibres (all working fibres having spare capacity for protection), and a U-SHR requires only two fibres (one working fibre and one protection fibre).

For each type of ring, two possible SONET self-healing control schemes may be used: line protection switching and path protection switching. The line protection switching schemes use SONET line overhead for protection switching and restores line demand from a failed facility, while the path protection switching scheme uses SONET path overhead, and restores individual end-to-end service channel. Today, only unidirectional rings with path protection switching and

bidirectional rings with line protection switching are commercially available. So a unidirectional self-healing ring (U-SHR) mentioned here is referred to as a unidirectional path-switched ring (UPSR). Similarly a
5 bidirectional self-healing ring (B-SHR) is referred to as a bi-directional line-switched ring (BLSR).

As shown in Figure 2 of the accompanying drawings, the U-SHR architecture uses only two fibres 1, with one for working traffic and the other for protection
10 traffic, and an ADM at each office or node 102. Each direction of a duplex channel travel on different routes between the two nodes 102 in the SHR. The self-healing capability is achieved by using low-speed path selection. The SONET U-SHR architecture discussed here
15 is based on a concept of signal dual-feed (1+1 protection). The architecture of such a ring consists of one ADM at each office or node 102 and a pair of fibres 1 with traffic on each fibre going in one direction.

In the U-SHR shown in Figure 2, a signal is to be transmitted from ADM A to ADM C. Each node 102 is connected to an adjacent node 102 in the ring by two optical fibres 1, with each of the two optical fibres 1
20 carrying signals in opposite directions. The signal from ADM A to ADM C is permanently bridged at ADM A such that two copies are sent to ADM C, one anti-clockwise around the ring on the inner ring fibre, and the other clockwise around the outer ring fibre. At
25 ADM C, each signal is detected by a detector 103, and the output of the detector 103 is used by a selector 104 to make the selection of one of the two possible received signals, which is then output from ADM C. If
30 there is a fibre cut at location X shown in Figure 2B, then only the clockwise signal will be detected by the detector 103, and this information will enable the
35 selector 104 to choose that signal permanently during

the period of the fibre cut.

The two-fibre B-SHR also uses two fibres. Unlike the U-SHR, however, the working and protection signals use the same fibre, with half the bandwidth reserved for protection; again, there is one ADM at each office. Half the bandwidth is reserved for working traffic, and the other half for protection traffic. This can be achieved, for example, by transmitting working traffic in even time slots and protection traffic in odd time slots, or can be achieved by using one range of wavelengths (for example upper wavelengths) for working traffic and a different range of wavelengths (for example lower wavelengths) for protection traffic.

Figure 3A of the accompanying drawings shows normal operation of a B-SHR. In a normal state, communication is conducted using only the working capacity, and as shown in Figure 3A, traffic can travel between ADM A and ADM C in both directions, with each direction of traffic travelling on a different ring. Selection circuitry, located for example in node A, would select the working path for transmission of signals from node A to node C, either via node B or via node D (usually the shortest of the two).

In this example, working traffic on the clockwise (outer) ring occupies lower wavelengths and working traffic on the anti-clockwise (inner) ring occupies the upper wavelengths. When there is a cable cut at location X marked in Figure 3B, for example, working traffic from ADM A destined for ADM C going anti-clockwise around the inner ring is rerouted onto the clockwise outer ring, using bandwidth reserved for the protection capacity. When the rerouted traffic reaches ADM D, it is switched back onto the inner ring working channel, to travel anticlockwise around the inner ring to reach its intended destination C. This means that the total number of spans progressed is four in the

protection case rather than two in the unprotected case. It can be seen that the protection operation is performed only by the two ADMs 202 on either side of the failed segment, which are those which can readily detect the failure. Both of those ADMs 202 are placed in "ring switch" mode, rerouting traffic away from the failed segment by using the protection capacity of the other fibre. They bridge traffic being sent towards the failed fibre over to the protection capacity and switch traffic coming from the protection capacity over to the working capacity. ADMs 202 on the protection path are placed in "full pass-through" state, by connecting the input and output channels.

An illustration of the bridging and switching operations performed by an ADM is shown in Figure 4 of the accompanying drawings. In the left-hand example, an ADM 202 is adding signals onto the top fibre going right, and dropping signals from the bottom fibre coming from the right. The right-hand example shows an illustration of the bridging and switching operations which should occur if there is, for example, a fibre failure to the right-hand side of the ADM 202. Traffic destined for the failed fibre is bridged onto the left-going bottom fibre, and traffic which was coming from the failed fibre and which has now been re-routed around the ring on the top fibre is switched out of the ring.

Generically for a ring of n nodes (n even) in the unprotected case the maximum number of spans is $n/2$, and the maximum number of spans in the protected case is $(3n/2-2)$, as shown in Figure 5 of the accompanying drawings.

Figure 6 of the accompanying drawings shows in more detail the components and operation of one of the nodes 202. Optical fibre E-F carries traffic in one direction around the ring, whilst optical fibre G-H

carries traffic in the opposite direction around the ring. In this example, signals are transmitted on a number of wavelengths λ_1 to λ_n . Working traffic in the direction E-F is carried on the upper half of the wavelength range, from $\lambda_{n/2+1}$ to λ_n , whilst the low range of wavelengths from λ_1 to $\lambda_{n/2}$ is reserved for protection traffic. Working traffic on the fibre in the direction G-H is carried using the low range of wavelengths from λ_1 to $\lambda_{n/2}$, whilst in that direction the upper wavelengths are reserved for protection traffic. In this way, each node allocates half the wavelengths to worker and half to protection. Each of the optical add/drop multiplexers 303 is operable to add/drop signals in the range of working wavelengths onto or off its respective fibre. Therefore, the optical add/drop multiplexer 303 on the fibre E-F adds/drops in the range $\lambda_{n/2+1}$ to λ_n , and the optical add/drop multiplexer 303 on the fibre G-H adds/drops in the range λ_1 to $\lambda_{n/2}$.

In normal operation, traffic is transmitted only on the working wavelengths, leaving the protection wavelengths free. Each optical switch 302 is normally in pass-through state, simply passing all signals straight through it. When there is a cable cut, for example, protection switching occurs and the wavelengths from one fibre are routed back around the ring on the other fibre. For example, if there is a cable cut occurring outside the illustrated node of Figure 6 on the F/G side, then high-wavelength working traffic on the E-F fibre is routed by optical switch F around onto the G-H fibre via optical switch G. Since this rerouted high-wavelength traffic is now travelling on the other fibre, it occupies the empty protection wavelengths. Likewise, if there is a cable cut, for example, on the E/H side then low-wavelength working traffic on wavelengths λ_1 to $\lambda_{n/2}$ is routed around onto

the low-wavelength protection channels going in the opposite direction on fibre E-F.

In the above-described B-SHR, bandwidth is shared between the working traffic and the protection traffic by using a different range of wavelengths for each of them. It is also possible to share bandwidth in other ways, for example by transmitting working traffic in odd time slots and protection traffic in even time slots along the fibre in one direction, and vice versa for the fibre carrying traffic in the opposite direction. In this way, if there is a fibre break or equipment failure, traffic is automatically switched into vacant time slots in the opposite direction to avoid the fault. It is also apparent that, although in normal operational mode the protection bandwidth is unused, this protection bandwidth may be used for normal working traffic if extra network capacity is needed.

Figure 7A of the accompanying drawings illustrates a four-fibre B-SHR. In such a network, the working and protection traffic travel on separate fibres. It is not only equipped with a ring switch, but also with a span switch, which is similar to 1:1 linear protection switching. If a failure occurs on a working fibre (marked at position X), the ADMs 222 on either side of the failure are placed in "span switch" state; they then switch the traffic from a failed fibre to a protection fibre on the same span, as illustrated in Figure 7B of the accompanying drawings. If a failure occurs on both working and protection fibres on the same span, as illustrated at position X in Figure 7C of the accompanying drawings, a ring switch is triggered instead of a span switch. The ADMs on either side of the failed segment reroute the affected traffic in the opposite direction away from the failure. The ADMs 222 on the protection path are placed on the "full pass-

through" state. Figure 8 of the accompanying drawings shows the internal operation of one of the ADMs 222 of Figure 7 for each state: normal (Figure 8A), span switch (Figure 8B) and ring switch (Figure 8C).

5 A U-SHR does not require any communications between nodes for protection switching, and is therefore more easily realised. However, it cannot use the bandwidth efficiently. The bandwidth requirement of the U-SHR is the maximum bandwidth requirement over
10 any span between any two nodes in the ring. No reuse of bandwidth is possible in a U-SHR network. Furthermore, it is impossible to transmit extra traffic, which is traffic transmitted on protection capacity only under normal conditions, because the
15 protection capacity is always used for the protection switching operation in a U-SHR network.

In the B-SHR architecture, the shorter path is used for normal communication and the longer path is used for backup. Communications between the two nodes
20 adjacent to the failure achieves this rerouting operation. The inter-nodal communication channel is accomplished via messages over the automatic protection channel. Since a B-SHR needs communications between nodes, a protection switching operation of a B-SHR is
25 more complex than that of a U-SHR. However, the B-SHR has the advantage of maximising bandwidth utilisation and has a higher capacity because the B-SHR provides the ability to reuse bandwidth and support extra traffic on the protection capacity.

30 The provision of network survivability such as that described above is essential in a reliable network. There are still a number of disadvantages associated with the operation of such network survivability procedures. Firstly, as illustrated in
35 Figure 5, in the worst case for a ring of n nodes the number of spans traversed by a signal increases

dramatically from $n/2$ spans to $3n/2-2$ spans. This increased path length can dramatically increase the dispersion experienced by a signal travelling on that path. Secondly, since in the above-described optical shared protection ring configuration where wavelength bandwidth is shared between protection and working capacity, wavelength sources are needed both in the high-wavelength range and in the low-wavelength range. In addition, differing ADM blocks need to be used for each of the working and protection directions.

According to an embodiment of a first aspect of the present invention there is provided an optical network comprising: a plurality of nodes, including a first node and a second node; a working path from said first node to said second node; a protection path, different from said working path, from said first node to said second node; wavelength conversion means; and switch means; wherein, during normal operation, working signals for transmission from said first node to said second node are transmitted via said working path, each such working signal having a wavelength within a working range of wavelengths; and wherein, during protection-switched operation, said switch means are operable to switch such working signals destined for said second node away from said working path and onto said protection path, and said wavelength conversion means are operable to convert such switched signals into protection signals, each such protection signal having a wavelength within a protection range of wavelengths, different from said working range of wavelengths, such that said protection signals can then be transmitted to said second node via said protection path.

According to an embodiment of a second aspect of the present invention there is provided an optical network comprising: a plurality of nodes, including a

first node and a second node; a working path from said first node to said second node; a protection path, different from said working path, from said first node to said second node; phase conjugation means; and
5 switch means; wherein, during normal operation, working signals for transmission from said first node to said second node are transmitted via said working path; and wherein, during protection-switched operation, said
10 switch means are operable to switch such working signals destined for said second node away from said working path and onto said protection path, and said phase conjugation means are operable to convert such
15 switched signals into protection signals having a phase-conjugate relationship to said working signals, such that said protection signals can then be transmitted to said second node via said protection path.

According to an embodiment of a third aspect of the present invention there is provided protection-switching circuitry for use in an optical network,
20 comprising: wavelength conversion means; and switch means; wherein, during normal operation, working signals for transmission from a first node of the network to a second node of the network are transmitted
25 via a working path between said first node and said second node, each such working signal having a wavelength within a working range of wavelengths; and wherein, during protection-switched operation, said
30 switch means are operable to switch such working signals destined for said second node away from said working path and onto a protection path between said first node and said second node, and said wavelength
35 conversion means are operable to convert such switched signals into protection signals, each such protection signal having a wavelength within a protection range of wavelengths, different from said working range of

wavelengths, such that said protection signals can then be transmitted to said second node via said protection path.

5 According to an embodiment of a fourth aspect of the present invention there is provided protection-switching circuitry for use in an optical network, comprising: phase conjugation means; and switch means; wherein, during normal operation, working signals for transmission from a first node of the network to a
10 second node of the network are transmitted via a working path between said first node and said second node; and wherein, during protection-switched operation, said switch means are operable to switch such working signals destined for said second node away
15 from said working path and onto a protection path between said first node and said second node, and said phase conjugation means are operable to convert such switched signals into protection signals having a phase-conjugate relationship to said working signals,
20 such that said protection signals can then be transmitted to said second node via said protection path.

25 According to an embodiment of a fifth aspect of the present invention there is provided a protection-switching method for use in an optical network, wherein: during normal operation, working signals for transmission from a first node of the network to a second node of the network are transmitted via a working path between said first node and said second
30 node, each such working signal having a wavelength within a working range of wavelengths; and wherein, during protection-switched operation, switch means of the network are operable to switch such working signals destined for said second node away from said working
35 path and onto a protection path between said first node and said second node, and wavelength conversion means

of the network are operable to convert such switched signals into protection signals, each such protection signal having a wavelength within a protection range of wavelengths, different from said working range of wavelengths, such that said protection signals can then be transmitted to said second node via said protection path.

According to an embodiment of a sixth aspect of the present invention there is provided a protection-switching method for use in an optical network, wherein: during normal operation, working signals for transmission from a first node of the network to a second node of the network are transmitted via a working path between said first node and said second node; and wherein, during protection-switched operation, switch means of the network are operable to switch such working signals destined for said second node away from said working path and onto a protection path between said first node and said second node, and phase conjugation means of the network are operable to convert such switched signals into protection signals having a phase-conjugate relationship to said working signals, such that said protection signals can then be transmitted to said second node via said protection path.

Reference will now be made, by way of example, to the accompanying drawings, in which:

Figure 1A shows a four-fibre bidirectional self-healing ring;

Figure 1B shows a two-fibre bidirectional self-healing ring;

Figure 1C shows a unidirectional self-healing ring;

Figure 2A shows normal operation of a unidirectional self-healing ring architecture;

Figure 2B shows the operation of a unidirectional

self-healing ring when a fibre cut occurs;

Figure 3A shows normal operation of a two-fibre bidirectional self-healing ring;

5 Figure 3B shows the operation of a bidirectional self-healing ring following a fibre cut;

Figure 4 shows the internal operation of an add/drop multiplexer of Figure 3;

Figure 5 shows the worst case working and protection routes;

10 Figure 6 shows the elements and operation of a node of Figure 3;

Figure 7A shows normal operation of a four-fibre bidirectional self-healing ring;

15 Figure 7B shows span switch operation of a four-fibre bidirectional self-healing ring;

Figure 7C shows ring switch operation of a four-fibre bidirectional self-healing ring;

Figure 8 shows the internal operation of a node in the Figure 7 ring architecture;

20 Figure 9A shows normal operation of an embodiment of the present invention before failure;

Figure 9B shows the operation of an embodiment of the present invention following a fibre cut;

25 Figure 10 shows the elements and operation of a node of Figure 9;

Figure 11A is a block diagram showing an optical phase conjugator;

Figure 11B is a diagram illustrating four wave mixing caused by an electro-optical effect;

30 Figure 11C is a diagram illustrating a frequency characteristic of an optical filter;

Figure 12A illustrates the principle of degenerate four wave mixing;

35 Figure 12B illustrates the principle of non-degenerate four wave mixing;

Figure 13A shows the worst case working and

protection routes; and

Figure 13B shows the worst case dispersion protection route.

Figure 9A shows the principle of operation of an embodiment of the invention during normal operation. Working traffic between two nodes may be carried in either direction, clockwise on the outer ring and anti-clockwise on the inner ring, as illustrated in Figure 9A. The components and operation are similar to the network shown in Figure 3A, but it can be seen that working traffic in an embodiment of the present invention is carried on the lower wavelengths in both directions. In the Figure 3A network, working traffic in one direction occupied the lower half of the wavelengths, whilst working traffic in the opposite direction occupied the upper half of the wavelengths. This was so that, in the event of a cable cut as illustrated in Figure 3B, working traffic in one direction which is re-routed around the other ring in the opposite direction does not interfere with the existing working traffic being carried in that direction.

The use of the same range of wavelengths for working traffic in both directions in an embodiment of the present invention is enabled by the use of wavelength converters in each node, as will be illustrated with reference to Figure 9B. In Figure 9B, a fibre cut has occurred between nodes A and D. In a similar way to the mechanism employed in the Figure 3 network, traffic from node A which is destined for node C in an anti-clockwise direction is rerouted clockwise around the other ring. Since working traffic in both directions occupies the same range of wavelengths, it is necessary to convert the working traffic wavelengths from one range to the other before it is rerouted onto the other fibre.

As an illustration, consider the traffic from node A to node C illustrated in Figure 9B. The normal route taken by such traffic is anti-clockwise around the ring to node C via node D. Due to the fibre cut between nodes A and D, this traffic is re-routed onto the clockwise path. Since all working traffic in both directions occupies the same range of wavelengths, a wavelength converter is used to place working wavelengths on the protection wavelengths prior to being re-routed in the opposite direction.

Figure 10 shows in more detail the components and operation of one of the nodes 402. Optical fibre E-F carries traffic in one direction around the ring, whilst optical fibre G-H carries traffic in the opposite direction around the ring, in a similar way to that shown in Figure 6. Working traffic in both directions is carried on the lower half of the wavelength range, from λ to $\lambda n/2$. The high range of wavelengths from $\lambda n/2 + 1$ to λn is reserved for protection traffic.

In normal operation, traffic is transmitted only on the working wavelengths, leaving the protection wavelengths free. The optical switches 502 are normally in a pass-through state, simply passing all signals straight through it. When there is a cable cut, for example, protection switching occurs and the wavelengths from one fibre are routed back around the ring on the other fibre, via a wavelength converter 505. The wavelength converter places working traffic onto the protection traffic range of wavelengths in the opposite direction.

Having the working traffic occupy the same range of wavelengths in both directions around the ring has two important advantages. Firstly, the number of working wavelengths is halved, reducing the number of laser sources required. Secondly, the ADM blocks in

each direction are adding/dropping the same wavelengths, allowing common parts to be used.

Wavelength conversion can be implemented using four wave mixing, enabling multiple wavelengths to be simultaneously converted. In addition, after conversion by four wave mixing, signals are a true spectrally inverted replica of the input signal, and in this way optical phase conjugation is achieved. This has the added advantage of reducing the end to end chromatic dispersion, as will be explained below.

The principle of four wave mixing, optical phase conjugation, and frequency conversion will first be explained. Figure 11A shows the basic components of a phase conjugator, and includes optical material 601 having an electro-optical effect, and an optical filter 602 for extracting phase conjugate light. In such a phase conjugator, when input signal light of a frequency f_s and pumping light of another frequency f_p are input to the optical material 601, four wave mixing is caused by an electro-optical effect of the optical material 601 so that, for example, light is output from the optical material 601 having frequencies f_c and f_n , different from the input frequencies f_p and f_s , as illustrated in Figure 11B.

The frequencies f_c and f_n in relation to the input signal light f_s and the pumping light f_p can be represented by the following equations:

$$f_c = 2f_p - f_s$$

$$f_n = 2f_s - f_p$$

Since the light having a frequency f_c has a phase inverted relationship to that of the input signal, it is in a phase conjugate relationship with the said input signal. However, the phase of the light having the frequency f_n is twice that of the input light and is not in an inverted relationship to that of the input light.

The signal output from the optical material 601 is input to the optical filter 602. The optical filter 602 has, for example, such a characteristic as illustrated in Figure 11C that it can extract phase conjugate light having the frequency f_c described above. In this way the input light signal having a frequency f_s has been frequency shifted to frequency f_c , and in addition is in a phase conjugate relationship to the input signal.

Four wave mixing can broadly be divided into two types: degenerate four wave mixing, and non-degenerate four wave mixing.

The principle of degenerate four wave mixing is illustrated in Figure 12A. In terms of photons, degenerate four wave mixing can be described as a parametric process where the energy from two pump photons, one from each wave, is converted into one probe and one output signal photon. It is a third-order non linear optical process involving the mixing of the four separate optical waves, which in the degenerate case all have the same frequency ω . The three input waves consist of two antiparallel high-power pump or reference waves and a weaker probe wave. The energy conservation requirement is obviously fulfilled in this case since all photons have the same frequency. To have an efficient energy transfer from the pumps to the probe and signal, there must also be momentum conservation. With k_1 , k_2 , k_p and k_s as the wave vectors of the two pumps, the probe, and the signal wave respectively, the so called phase-matching condition means that $k_1 + k_2 = k_p + k_s$. Since the two pump photons are anti-parallel, with zero total momentum ($k_1 + k_2 = 0$), this means that the signal wave must be anti-parallel to the probe wave, as shown graphically in Figure 12A. Momentum conservation is the basis of the phase-conjugate nature of the output

signal. The output signal is proportional to the complex conjugate of the probe field. It is also possible to have four wave mixing optical phase conjugation process with amplification.

5 The degenerate four wave mixing process yields a conjugated output wave at the same wavelength as the probe wave. To achieve phase conjugation with frequency conversion, non-degenerate four wave mixing can be used. The principle of non-degenerate four wave
10 mixing is illustrated in Figure 12B. In this case, the two pump photons carry a non-zero total momentum in the z direction. That is tuned to match the frequency difference of the probe and signal waves.

15 There are many other non-linear optical processes that are capable of generating a phase-conjugate wave. Holography can be considered as a static form of phase conjugation. The reconstructed field that forms a real image in conventional holography is actually a phase-conjugate replica of the original object field.

20 Stimulated scattering processes are another important class of interactions that can be used for optical phase conjugation. Scattering can be described as a two-photon process where a probe photon is absorbed and a frequency-shifted scattered signal photon is emitted,
25 whilst the material makes a transition to an excited state. Examples of this include stimulated Brillouin scattering, and stimulated Raman scattering. Multiwave mixing, involving a number of waves not equal to four, is also possible (for example three-wave mixing and
30 six-wave mixing).

 Nonlinearities in semiconductor optical amplifiers can also be exploited in other ways to perform wavelength conversion, e.g. cross-gain modulation (XGM) and cross-phase modulation (XPM). Other wavelength
35 conversion devices are expected in the near future.

 As a lightwave pulse of given pulse duration and

given spectral line width travels down an optical fibre, the different wavelengths experience different refractive indices and therefore propagate at different speeds, causing pulse broadening as the pulse propagates along the fibre because the different wavelengths that make up the spectral line width arrive at the far end at different times. Dispersion imposes a limit on the bit-rate x length product (BRLP) for digital data and band width for analog data transmitted in an optical fibre for a given bit error ratio (BER) at the limit of inter symbol interference. Waves of different wavelengths are shifted in phase over given lengths of the fibre by different amounts because of their different propagation velocities giving rise to distortion of signals.

During normal uninterrupted operation in a self-healing ring, traffic between two nodes in the ring usually travels by the shortest path, thus reducing the effects of dispersion. When protection switching is in operation following a fibre cut, for example, the path length is increased as the signals are re-routed on a different path. For example, in Figure 3A signals travelling from node A to node C in normal operation traverse two spans, whilst in Figure 3B, following a fibre cut, this is increased to four spans, and the effects of dispersion are therefore doubled.

By the use of phase conjugating wavelength converters as explained above, the effect of this increased path length on the overall dispersion can be reduced. Since signals on the protection path are a true spectrally inverted replica of the signals travelling on the working path, the chromatic dispersion due to propagation in the working path is compensated by the chromatic dispersion in the protection path. The equivalent overall chromatic dispersion effect is equivalent to the difference

between the two path lengths. In the example shown in Figure 9B, signals travelling from node A to node C travel three spans on the protection path, and one span on the working path, so that the overall chromatic dispersion effect is equivalent to that of two spans.

With reference to Figure 13A, it can be seen that for a ring of n nodes (n even) the maximum number of spans in the unprotected case of the working route is $n/2$, which occurs when routing to a node half-way around the ring. The worst case protection route occurs when the fibre cut occurs adjacent to the source node, as shown in Figure 13A, resulting in the protection path covering $3n/2 - 2$ spans. However, the dispersion effect for this worst case is reduced from $3n/2 - 2$ to $n/2$. The worst case dispersion will occur when routing to the node adjacent to the failure, as shown in Figure 13B, where the maximum number of spans is $n-1$ and there is no reduction in the dispersion effect using the above-described wavelength conversion method.

Although the Figure 9 optical ring network employs wavelength converters 405 which also provide optical phase conjugation, it is also possible to achieve some advantage by the use of wavelength converters which do not perform optical phase conjugation, and also optical phase conjugators which do not perform wavelength conversion.

For example, in the Figure 3 network, if rerouted signals are passed through an optical phase conjugator prior to being rerouted, then some dispersion reduction benefit will be gained. If in the Figure 9 network the wavelength converter 405 simply converted wavelengths but did not perform optical phase-conjugation, then the above-stated benefit of reducing the number of working wavelengths would still be achieved. These methods could also be used in other network protocols and

architectures, for example in the above-described four-fibre network architecture.

The above-described embodiment of the invention has been described with reference to a two-fibre optical network, wherein following a failure to the working fibre between nodes A and D (see Figure 9B), protection signals travel the opposite way around the ring on the protection fibre via node B, through node C and onto node D, the latter node being adjacent to the fibre failure and therefore readily able to have knowledge of the fibre failure. At node D the signals are wavelength converted and switched back onto the working path for onward transmission to intended node C. It is also possible to have a separate protection path between nodes A and D which does not travel all the way around the ring through node C. For example, the protection path may simply span nodes A and D directly, so that protection signals travel direct from node A to node D, before conversion and switching for onward transmission to node C via the working path. This would be the case, for example, in the four-fibre network shown in Figure 7B, where a failure occurs to the working path between nodes A and D, but since an unaffected protection path is available direct from node A to D, protection signals are routed direct on that path, rather than travelling all the way around the ring in the opposite direction. When there is more than one protection path available, selection circuitry would select the protection path to be used for transmission, for example the shortest protection path.

CLAIMS

1. An optical network comprising:

a plurality of nodes, including a first node and a second node;

5 a working path from said first node to said second node;

a protection path, different from said working path, from said first node to said second node;

wavelength conversion means; and

10 switch means;

wherein, during normal operation, working signals for transmission from said first node to said second node are transmitted via said working path, each such working signal having a wavelength within a working range of wavelengths; and

15 wherein, during protection-switched operation, said switch means are operable to switch such working signals destined for said second node away from said working path and onto said protection path, and said wavelength conversion means are operable to convert such switched signals into protection signals, each such protection signal having a wavelength within a protection range of wavelengths, different from said working range of wavelengths, such that said protection signals can then be transmitted to said second node via said protection path.

2. An optical network according to claim 1, further comprising:

30 a further working path from said second node to a further node of the network;

additional wavelength conversion means; and

additional switch means;

35 wherein said additional switch means are operable to switch such protection signals arriving at said second node, via said protection path, onto said further working path, and said additional wavelength

conversion means are operable to convert such switched signals into further working signals, each such further working signal having a wavelength within said working range of wavelengths, such that said further working signals can then be transmitted to said further node via said further working path.

3. An optical network according to claim 2, wherein said additional wavelength conversion means are located within said second node.

4. An optical network according to claim 1, 2 or 3, wherein the wavelength-converted signals output from said wavelength conversion means are in a phase conjugate relation to the signals input to said wavelength conversion means.

5. An optical network according to any one of claims 2 to 4, wherein the wavelength-converted signals output from said additional wavelength conversion means are in a phase conjugate relation to the signals input to said additional wavelength conversion means.

6. An optical network according to any preceding claim wherein said wavelength conversion means are located within said first node.

7. An optical network according to any preceding claim, further comprising optical add/drop multiplexer means which are operable to multiplex signals having wavelengths within said working range onto said working path.

8. An optical network according to any preceding claim, further comprising optical add/drop multiplexer means which are operable to demultiplex signals having wavelengths within said working range off said working path.

9. An optical network according to any preceding claim, wherein said wavelength conversion means employ the four wave mixing method to perform wavelength conversion.

10. An optical network according to any one of claims 1 to 8, wherein said wavelength conversion means employs cross-gain modulation to perform wavelength conversion.

5 11. An optical network according to any one of claims 1 to 8, wherein said wavelength conversion means employs cross-phase modulation to perform wavelength conversion.

10 12. An optical network according to any one of claims 1 to 8, wherein said wavelength conversion means employs Brillouin scattering to perform wavelength conversion.

15 13. An optical network according to any one of claims 1 to 8, wherein said wavelength conversion means employs Raman scattering to perform wavelength conversion.

14. An optical network comprising:

a plurality of nodes, including a first node and a second node;

20 a working path from said first node to said second node;

a protection path, different from said working path, from said first node to said second node;

phase conjugation means; and

25 switch means;

wherein, during normal operation, working signals for transmission from said first node to said second node are transmitted via said working path; and

30 wherein, during protection-switched operation, said switch means are operable to switch such working signals destined for said second node away from said working path and onto said protection path, and said phase conjugation means are operable to convert such switched signals into protection signals having a
35 phase-conjugate relationship to said working signals, such that said protection signals can then be

transmitted to said second node via said protection path.

15. An optical network according to claim 14, further comprising:

5 a further working path from said second node to a further node of the network;

additional phase conjugation means; and

additional switch means;

10 wherein said additional switch means are operable to switch such protection signals arriving at said second node, via said protection path, onto said further working path, and said additional phase conjugation means are operable to convert such switched signals into further working signals having a phase-
15 conjugate relationship to said protection signals, such that said further working signals can then be transmitted to said further node via said further working path.

16. An optical network according to claim 15, wherein
20 said additional phase conjugation means are located within said second node.

17. An optical network according to any one of claims 2 to 13, 15 or 16, wherein said additional switch means are located within said second node.

25 18. An optical network according to any preceding claim, wherein said protection path and said working path take different geographical routes from said first node to said second node.

30 19. An optical network according to any preceding claim, wherein said switch means are located within said first node.

20. An optical network according to any preceding claim, wherein there is a plurality of candidate working paths between said first node and said second
35 node, and the network further comprises working path selection means which are operable to select said

working path to be used for transmission of working signals from said first node to said second node.

21. An optical network according to claim 20, wherein the number of such candidate working paths is two.

5 22. An optical network according to claim 20 or 21, wherein said working path selection means are located within said first node.

23. An optical network according to claim 20, 21 or 22 wherein said working path selection means are operable
10 to select the shortest working path between said first node and said second node.

24. An optical network according to any preceding claim, wherein there is a plurality of candidate protection paths between said first node and said
15 second node, and the network further comprises protection path selection means which are operable, during protection-switched operation, to select said protection path to be used for transmission of protection signals from said first node to said second
20 node.

25. An optical network according to claim 24, wherein the number of such candidate protection paths is two.

26. An optical network according to claim 24 or 25, wherein said protection path selection means are
25 located within said first node.

27. An optical network according to claim 24, 25 or 26 wherein said protection path selection means are operable to select the shortest protection path between said first node and said second node.

30 28. An optical network according to any preceding claim, wherein a working path may occupy the same physical optical fibre as a protection path.

29. An optical network according to any preceding claim, wherein certain of said working signals
35 originate from within said first node.

30. An optical network according to any preceding

claim wherein certain of said working signals are received by said first node from another node of the network.

5 31. An optical network according to any preceding claim, wherein said working path between said first node and said second node includes one or more other nodes of the network along its length.

10 32. An optical network according to any preceding claim, wherein said protection path between said first node and said second node includes one or more other nodes of the network along its length.

15 33. An optical network according to any preceding claim, wherein protection-switched operation is enabled following a working path failure occurring between said first node and said second node.

34. An optical network according to claim 33, wherein said first node is directly adjacent to said working path failure.

20 35. An optical network according to claim 33 or 34, wherein said second node is directly adjacent to said working path failure.

36. An optical network according to any preceding claim, wherein said plurality of nodes are arranged in a ring formation.

25 37. Protection-switching circuitry for use in an optical network, comprising:

wavelength conversion means; and
switch means;

30 wherein, during normal operation, working signals for transmission from a first node of the network to a second node of the network are transmitted via a working path between said first node and said second node, each such working signal having a wavelength within a working range of wavelengths; and

35 wherein, during protection-switched operation, said switch means are operable to switch such working

signals destined for said second node away from said working path and onto a protection path between said first node and said second node, and said wavelength conversion means are operable to convert such switched signals into protection signals, each such protection signal having a wavelength within a protection range of wavelengths, different from said working range of wavelengths, such that said protection signals can then be transmitted to said second node via said protection path.

38. Protection-switching circuitry for use in an optical network, comprising:

phase conjugation means; and
switch means;

wherein, during normal operation, working signals for transmission from a first node of the network to a second node of the network are transmitted via a working path between said first node and said second node; and

wherein, during protection-switched operation, said switch means are operable to switch such working signals destined for said second node away from said working path and onto a protection path between said first node and said second node, and said phase conjugation means are operable to convert such switched signals into protection signals having a phase-conjugate relationship to said working signals, such that said protection signals can then be transmitted to said second node via said protection path.

39. A protection-switching method for use in an optical network, wherein:

during normal operation, working signals for transmission from a first node of the network to a second node of the network are transmitted via a working path between said first node and said second node, each such working signal having a wavelength

within a working range of wavelengths; and

wherein, during protection-switched operation, switch means of the network are operable to switch such working signals destined for said second node away from said working path and onto a protection path between said first node and said second node, and wavelength conversion means of the network are operable to convert such switched signals into protection signals, each such protection signal having a wavelength within a protection range of wavelengths, different from said working range of wavelengths, such that said protection signals can then be transmitted to said second node via said protection path.

40. A protection-switching method for use in an optical network, wherein:

during normal operation, working signals for transmission from a first node of the network to a second node of the network are transmitted via a working path between said first node and said second node; and

wherein, during protection-switched operation, switch means of the network are operable to switch such working signals destined for said second node away from said working path and onto a protection path between said first node and said second node, and phase conjugation means of the network are operable to convert such switched signals into protection signals having a phase-conjugate relationship to said working signals, such that said protection signals can then be transmitted to said second node via said protection path.

41. An optical network substantially as hereinbefore described with reference to Figures 9 to 13 of the accompanying drawings.

42. Protection-switching circuitry substantially as hereinbefore described with reference to Figures 9 to

13 of the accompanying drawings.

43. A protection-switching method substantially as hereinbefore described with reference to Figures 9 to 13 of the accompanying drawings.



Application No: GB 9911200.5
Claims searched: 1, 37, 39 and claims
dependent thereon

Examiner: Stephen Brown
Date of search: 26 August 1999

Patents Act 1977 Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.Q): H4B (BK20, BKX, BN), H4P (PPD).

Int Cl (Ed.6): H04B: 10/20, H04J: 14/02.

Other: Online: WPI, EPODOC, JAPIO.

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
X	EP 0 620 694 A2 (NEC) See especially column 9, line 15, to column 10, line 25.	1, 37, 39 at least.
X	WO 97/25829 A2 (MCI) See especially figures 5 & 6, and page 14, line 7, to page 15, line 19.	1, 37, 39 at least.

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Application No: GB 9911200.5 Examiner: Stephen Brown
Claims searched: 14, 38, 40 and claims dependent thereon Date of search: 7 March 2000

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Further Search Report under Section 17

Databases searched:

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UK CI (Ed.R): H4B (BK20, BKX, BN), H4P (PPD).

Int CI (Ed.7): H04B: 10/20, H04J: 14/00, H04L: 12/437.

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Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	EP 0 620 694 A2 (NEC) See especially column 9, line 15, to column 10, line 25.	-

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
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